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AVCO
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LABORATORY

a division of
AVCO CORPORATION

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FINAL REPORT

Contract No. NAS w-748

July 1964

prepared for

HEADQUARTERS
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
Washington 25, D. C.

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Everett, Massachusetts

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PREFACE

This final report has been prepared as a brief review of work performed under the subject contract. In the belief that the eight papers prepared under the contract have been written in such a way as to exhibit as clearly as possible their respective achievements and results, and since these papers report in detail the overwhelming majority of the work performed under the contract, these papers are attached to this final report. In the pages that follow the papers are put into a general perspective and in each case the abstract is quoted in full. In addition, various items of work which did not terminate in full length papers are briefly discussed.

I. TOTAL HEAT TRANSFER MEASUREMENTS

The heat transfer experiments under this contract have fallen somewhat short of expectations. It was assumed at the start of this experiment that the infrared heat transfer gage, developed and used by Camac in end wall heat transfer experiments under somewhat less severe conditions, could be readily adapted to making quantitative convective heat transfer measurements as well as total heat transfer measurements which would yield the radiative flux by subtraction. However, the demands made on the gage by the present experiments were considerably more extreme than previous experience. The required opacity of the gage was only achieved by overcoating the carbon with a metallic film and thus a three-layer gage was required for total heat transfer measurements. A number of difficulties with gage response, calibration, and gage manufacturing were overcome.

Convective heat transfer measurements were made with metallic films of various materials overcoating the carbon. These experiments and the experimental details of the measurements are reported in Ref. 1, the abstract of which follows:

Heat Transfer Experiments in Partially Ionized Gases

P. H. Rose and J. O. Stankevics

Over the past few years a number of theoretical and experimental investigations have been published on the subject of convective energy transport in a high temperature partially ionized gas. Although, in general a fair degree of understanding of this process is now available, certain uncertainties have arisen, particularly with respect to the effect of the surface material of the heat transfer gage. This experimental investigation brings a new technique of making heat transfer measurements to bear on this problem.

The infrared heat transfer gage developed by Camac has been adapted to the problems peculiar to this experiment. An analysis is presented which demonstrates the response required of the measurement in order to enable accurate heat transfer measurements to be made within the limited test times available. The difficulties of adapting the gage to the requirements are described, in particular the sensitivity, opacity, and adherence of the gage to the MgO window. The calibration of the absolute magnitude of the output of the infrared cell as well as the response time of the measuring system are described in detail. The response of the gage to the heat transfer encountered in both the shock tube end wall and on a model are discussed with emphasis on the identification of radiative heat transfer effects.

The heat transfer results support the previous results of the authors with calorimeter gages as well as those of other investigations. Variations of the gage surface material achieved by overcoating the carbon with thin metallic films did not change the heat transfer rates measured, in contrast to the results reported by Warren. In view of the fact that the metallic films used do not change the calibration of the gage this is felt to be a conclusive result regarding the effect of surface materials.

The development of the infrared heat transfer gage for total heat transfer measurements was essentially completed. A number of three layer gages were made and indicated the expected response. A clear method of differentiation between transmitted light and radiative heating was still under development. The so-called knife edge model was developed to aid in the differentiation of radiative and convective heating. Several experimental records were made with this arrangement but analysis of the data was not completed. It appears that most of the obstacles in obtaining these data have been overcome, but a continuation of this work to verify the soundness of this approach would be desirable.

II. CONVECTIVE HEAT TRANSFER

A study has been undertaken of the effect on an argon boundary layer of a finite rate of energy exchange between heavy particles and electrons. In addition to the usual effects in an ionizing boundary layer, this introduces the additional complication of different temperatures for the heavy particles and the electrons.

A preliminary report on the investigation has been issued,[2] whose abstract follows:

A Multitemperature Boundary Layer

M. Camac and N. H. Kemp

This is a preliminary report on an analytical investigation of the end wall boundary layer behind a reflected shock in a shock tube in highly ionized argon. Two nonequilibrium effects are considered: (1) chemical nonequilibrium because of finite recombination rates; and (2) lack of equilibrium between electron and heavy (atom and ion) particle temperatures because of a finite rate of energy exchange by elastic collisions between electrons and ions. In contrast with previous work in this area, we retain the coupling between the electrical and the aerodynamic effects, considering both simultaneously. The boundary layer is divided into two regions. Near the wall there is a plasma sheath whose thickness is several Debye lengths. The Debye length is small compared to the boundary layer thickness. In this sheath, the simple molecular description of the plasma originated by Langmuir and Mott-Smith is used. Outside the sheath, in the aerodynamic boundary layer, the usual continuum fluid mechanics treatment is used. These two descriptions of the plasma are joined at the sheath edge by requiring continuity of ion mass flux and electron energy flux, which serve as boundary conditions for the continuum boundary layer equations. The basic information determining the chemical kinetics and transport properties of ionized argon are well known, and they are employed to develop the set of boundary layer equations for the two-temperature case considered here. The solution of these equations is attempted by means of a local similarity approach, in which time is treated as a parameter, and the boundary layer equations are reduced to ordinary differential equations. Only a few solutions, all for frozen chemistry, are available at this stage of the investigation.

They show that when elastic energy exchange between ions and electrons is ignored, the electron temperature at the sheath edge is about half the external temperature. However, the solutions for no and complete elastic energy exchange show only a slight difference on the wall heat transfer rate. Further calculations for both frozen chemistry and finite recombination rate cases will be pursued.

Since this report was written, further work has been confined to study aimed at overcoming numerical difficulties which developed when calculations were attempted. These difficulties are associated with the use of matching procedures to solve ordinary differential equations with two-point boundary values when the equations contain source terms due to chemical reactions and/or energy interchange between electrons and heavies.

First, a procedure developed for Paul Chung at the Aerospace Corporation was investigated.[3] This involves a finite difference scheme, guessing profiles, and successive approximations. Study of this method showed it to be useful but fairly complicated.

About the time the Aerospace method was digested, some recent developments in the solution of chemically non-equilibrium boundary layers in two independent variables became available.[4] A brief look gave us reason to think they could be applied to our problem with little or no more work than in the Aerospace method. A further advantage is that the inclusion of two independent variables may make it possible to relax the local similarity approximation made in Ref. 2 for the purpose of obtaining ordinary differential equations. We may be able to solve instead the exact two-variable problem. Study has begun of this method. When we have digested it, we will consider its applicability to the two-temperature argon boundary layer.

III. RADIATION IN NITROGEN - CO_2 MIXTURES

Nitrogen plus carbon dioxide mixtures have been heated in both incident and reflected shock waves to temperatures up to 8000°K and densities up to normal.

The reflected shock experiments have been made in a steel shock tube, 10 feet long, 1-1/2 inches diameter, with an end plate containing a window for axial viewing of the gas. A rotating drum camera spectrograph was used for qualitative surveys of the spectrum and a rapid scanning photoelectric spectrometer was used for absolute intensity measurements.

The incident shock experiments have been made in the steel tube with a round to square transition block and an old schlieren window block for transverse viewing and, more recently, with a glass tube, fitted with thin film platinum heat transfer gauges. Spectrograms have been obtained with a small quartz spectrograph and intensity measurements have been made with the scanning instrument and a monochromator built for the purpose.

The spectral range investigated has extended from 0.2 to 1.2μ. (At 8000°K about 90% of the black body radiation lies in this region.) The CN radicals dominated the spectrum, in the blue in three well-defined regions (the CN violet system), and in the red from 0.6 to 1.2μ in a fairly continuous coverage (the CN red system). The other molecular radiator of importance was the C_2 radical.

Since the radiative transition probability for the CN red system was quite unknown, the first work was concentrated on measuring this. Both incident and reflected shock measurements were made. The experimental data were reduced with the aid of a machine computation of the equilibrium conditions. The dissociation energy of CN was not known with certainty and values of 7.60 ev and 8.35 ev were used. The following table lists the results obtained. The transition probability is given as the Einstein value.

CN RADIATION

	Red $\lambda = 1.1\mu$	
D_o (ev)	A (S^{-1}) $\pm$ 50%	shock
8.35	1.9×10^5	reflected
7.6	4.3×10^5	
8.35	1.1×10^5	incident
7.6	3.3×10^5	
	Violet $\lambda = 0.42\mu$	
8.35	6×10^6	reflected
7.60	1.2×10^7	

It had been hoped that variation of the shock conditions would allow a choice between the dissociation energies but the scatter in the data was too great for the fairly limited range of experimental conditions available. In passing, it may be noted that some recent work[5] has agreed better with the results corresponding to D_o CN = 7.60 ev.

This work on CN has been sent to the AIAA Journal and is now published.[6] The abstract of this paper follows:

The Spectrum of Shock-Heated Gases Simulating
the Venus Atmosphere

A. Fairbairn

Mixtures of 90% N_2 plus 10% CO_2, and 80% N_2 plus 20% CO_2 have been heated by reflected shock waves to temperatures of about 8000°K and normal density. Photographic and photo-electric measurements have been made of the emitted radiation in the region of 0.23μ to 1.2μ. The CN radical is the most prominent radiator in these experiments and the intensity of the emission has been used to derive transition probabilities for the violet and red systems of bands.

Subsequent work to measure the C_2 transition probabilty has given a good deal more trouble than was originally anticipated. It was observed in the early work that CO, a decomposition product of CO_2, gave strong C_2 radiation when heated and spectrograms showed the C_2 bands "cleanly", i.e., not mixed with other radiation.

There is virtually no reliable information on the radiative transition probability of C_2. Theoretical estimates[7] have ranged from 2.4×10^{-1} to 2×10^{-2}. Experimental estimates vary from 2×10^{-4} (Ref. 8) to 3.4×10^{-2} (Ref. 9) and so it was decided to follow these observations with measurement on the monochromator using incident shock waves in the glass tube. Much difficulty was experienced with the heat gages. A strong radiative overshoot was obtained at the shock front and it was suspected to be spurious. The cause was finally traced to a trace impurity in the CO being used but it proved impossible to eliminate, even with distillation at liquid nitrogen temperatures. The impurity was not identified but had certain very strong infrared absorption and was definitely organic. This gas was later replaced by a fresh supply which did not contain this contaminant. Some measurements have been obtained and reduced with the aid of the requisite equilibrium calculations to obtain a rough value of $A = 1.5 \times 10^7$ for the Swan bands, corresponding to an f number of 5×10^{-2}.

IV. SHOCK FRONT STUDIES

Under this heading a paper has been written.[10] The abstract of this paper follows:

Nonequilibrium Shock Front Rotational, Vibrational and Electronic Temperature Measurements

R. A. Allen

A spectroscopic technique is described for measuring nonequilibrium shock front rotational, vibrational and electronic temperatures. This method uses a triple channel monochromator which is able to resolve the vibrational structure of diatomic molecular radiation, and a monitor channel to observe an electronic transition composed of many vibrational transitions. Measurements are made on incident nitrogen shock waves by observing the $\Delta v = +1$ sequence of the $N_2^+(1-)$ and $N_2(1+)$ systems. As well as giving nonequilibrium temperature results, this experiment has given equilibrium radiation intensities which indicate an f number at the 0, 0 transition of .035.

This paper is to be given at the Third National Meeting of the Society of Applied Spectroscopy; it is also being submitted to the Journal of Quantitative Spectroscopy and Radiative Transfer.

V. MAGNETOHYDRODYNAMICS

Experiments to determine the flow of an ionized gas over a wire carrying a current and producing a magnetic field sufficient to separate the shock layer from the wire have been performed. These experiments which are reported in Ref. 11, were compared successfully with the theory of Levy and Petschek.[12] The abstract of the experimental paper follows:

Experiments with Magnetohydrodynamically
Supported Shock Layers

E. Locke, H. E. Petschek and P. H. Rose

Shock tube experiments have been performed to quantitatively determine the interaction of a hypersonic flow with the magnetic field of a straight current-carrying wire oriented perpendicular to the flow direction. The interaction which takes place in a thin layer behind a detached shock wave is subject to the following restrictions: (1) Negligible conductivity upstream of the shock; (2) Low magnetic Reynolds number and scalar conductivity in the shock layer. The straight wire geometry under these restrictions has been analyzed theoretically by Levy and Petschek. The analysis, which is briefly reviewed, predicts the location of a thin shock layer which is concentric with the wire.

Most of the experimental work was performed in a 50-50 mixture of argon and oxygen, at an initial pressure of 1 mm Hg, and in a range of shock velocities between 4.3 and 6 mm/μsec. Data have been obtained by observing the flow luminosity, using an image converter and mirror camera looking both perpendicular to and along the wire. A circular shock front was observed to stand up to 5-1/2 cm in front of a 1 cm radius cylinder producing the magnetic field. The data on shock position vs current were in excellent agreement with theory in spite of the fact that values of ϵ equal to 0.25 resulted in theoretical accuracies only to within a factor of two.

It is anticipated that this paper will be submitted to Physics of Fluids for publication.

Theoretical considerations of the type described in Ref. 12 have been extended to a more complex but more realistic geometry, namely that of a dipole flying with its axis aligned parallel to the flow. A paper[13] describing this work has been written and will appear shortly in the Journal of the AIAA. The abstract of this paper follows:

Hypersonic Magnetohydrodynamics with or without A Blunt Body

R. H. Levy, P. J. Gierasch, and D. B. Henderson

We consider the hypersonic flow of a cold gas past a two-dimensional or axially symmetric body containing a two or three-dimensional magnetic dipole with its axis oriented parallel to the flow. The magnetic moment of the dipole and the size of the body are of arbitrary proportions. A uniform scalar conductivity is turned on by the shock, and the magnetic Reynolds number is low. For low values of the interaction parameter the flow is quasi-aerodynamic. Certain discrepancies existing in the literature on the flow in this regime are reconciled. At high values of the interaction parameter the nature of the flow is quite different. In this regime it consists of a thin deceleration layer (somewhat akin to the aerodyanmic shock layer) and an extensive region of low Mach number flow (called the slow flow region) which separates the deceleration layer from the body. The gas in the slow flow region escapes outward at sonic velocity along the field lines. In some circumstances the entire flow field can be supported by the magnet, i.e., without the hot gas touching the body. Assuming a large compression ratio across the shock a relatively simple analysis can be performed. Calculations covering various representative cases are exhibited; the validity and significance of these calculations are discussed.

Arising out of this work, a short paper on a related topic in MHD was written[14] and has been published in the Physics of Fluids. This paper is distinguished from Ref. 13 by being at high magnetic Reynolds number. The abstract of this paper follows:

Interaction of A Streaming Plasma with The Magnetic Field of a Two-Dimensional Dipole

R. H. Levy

The flow of an infinitely conducting plasma past a two-dimensional magnetic dipole oriented parallel to the flow has been considered by Hurley, amongst others. The problem consists of finding a vacuum magnetic field such that along a bounding field line whose location is to be found, the magnetic pressure balances the Newtonian dynamic pressure appropriate to the local slope of the boundary. A related problem has been solved by Cole and Huth; in their case there is no flow, but an isotropic static plasma surrounding the magnetic field region which exerts a constant pressure on the boundary. In the actual flow problem we would expect there to be a stagnant (trapped) region near the front. The stagnant flow would be at nearly constant pressure. Away from this region the Newtonian pressure would again be applicable. This problem, which is a mixture of those cited above, has been solved by an approximate technique due to Cockcroft. The solution is shown to have features of both the cited problems, as appropriate.

Work was also performed on a preliminary attempt to estimate the usefulness in two particular re-entry configurations of practical flight MHD devices based essentially on the descriptions of the flow given in Ref. 13 and 14. The abstract of this paper follows:

On the Use of Magnetohydrodynamics During High Speed Re-entry

P. O. Jarvinen

The use of the interaction of a magnetic field with a hypersonic flow, to effect the decelerations and heating encountered during re-entry is considered. The equations of motion which describe the re-entry history of non-lifting vehicles employing magnetohydrodynamic interactions with the flow field are simplified in the manner of Allen and Eggers. Analytical expressions are derived for the velocity history, deceleration history, and the altitude and magnitude of peak heating and deceleration for re-entries involving both low or high magnetic Reynolds number interactions. In both cases it is found that the maximum heating and deceleration experienced can be reduced significantly below that encountered by purely aerodynamic vehicles.

Vertical re-entries at velocities of 40, 000 and 50, 000 feet per second are considered. Solutions for the trajectories require the use of high magnetic Reynolds number theory initially with transition to low magnetic Reynolds when both theories predict equivalent drag areas. The drag area predicted by the low magnetic Reynolds number theory decreases more rapidly with altitude than that predicted on the basis of high magnetic Reynolds number. This reduces the maximum decelerations encountered below the values predicted by the purely high magnetic Reynolds number theory. A reduction in peak deceleration of about 35 percent was achieved due to the magnetohydrodyanmic interaction. Significant reductions in heating were also achieved.

A comparative study of magnetohydrodynamic and aerodynamic vehicles was performed for lifting re-entries with lift to drag ratios

from 1/2 to 4, typical of manned return from Mars or Venus. Use of magnetohydrodynamic interaction significantly widens the re-entry corridor and decreases the re-entry heating. On the undershoot boundary the heat load experienced by the magnetohydrodynamic vehicle is one order of magnitude less than that of the aerodynamic vehicle while on the overshoot boundary, it is two orders of magnitude less. It was found that in general, estimated weights of the magnetic coils needed to produce the magnetohydrodynamic interaction were considerably smaller than the heat protection weight required without the magnetic field.

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